ICME Guided Development of Advanced Cast Aluminum Alloys For Automotive Engine Applications

Project ID: MAT060

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Ford Motor Company

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Overview

Timeline

- Project start date: February 2013
- Project end date: August 2018
- Percent complete: 100%

Barrier

- High temperature performance
- Design data & modeling tools
- Manufacturability
- Cost

Budget

- Total project funding
  - ➢ DOE share: $3.24M
  - ➢ Contractor share: $1.39M
- Funding received in FY17
  - ➢ $716K
- Funding for FY18
  - ➢ $0

Partners

- Alcoa Inc.
- Nemak
- MAGMA Foundry Technologies, Inc.
- University of Michigan

Project Objectives

- To develop a new class of advanced, cost competitive aluminum casting alloys providing a 25% improvement in component strength relative to components made with A319 or A356 alloys for high-performance engine applications.

- To demonstrate the power of Integrated Computational Materials Engineering (ICME) tools for accelerating the development of new materials and processing techniques, as well as to identify the gaps in ICME capabilities.

- To develop comprehensive cost models to ensure that components manufactured with these new alloys do not exceed 110% of the cost using incumbent alloys A319 or A356.

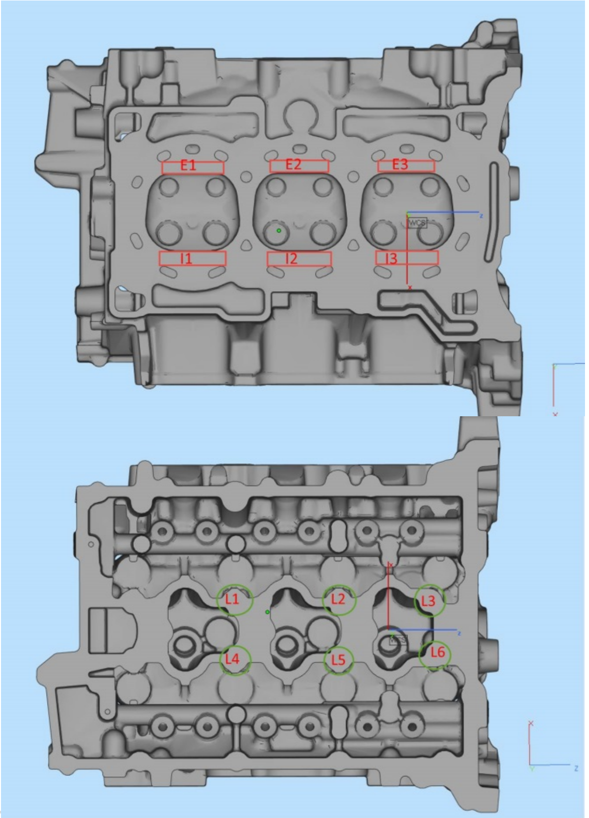
- To develop a technology transfer and commercialization plan for deployment of these new alloys in automotive engine applications.

Outline

- Alloy Design Approach
- Experiments
  - Microstructure Characterization
  - Mechanical Properties
- Prototyping
  - 1.5L GTDI Dragon Heads
  - 2.0L GTDI Duratec Bearing Beam
- ICME Tools Development and Gap Identification
  - Solidification
  - Solution treatment
  - Precipitates kinetics
  - Casting process simulation
- Cost Model Development
- Summary

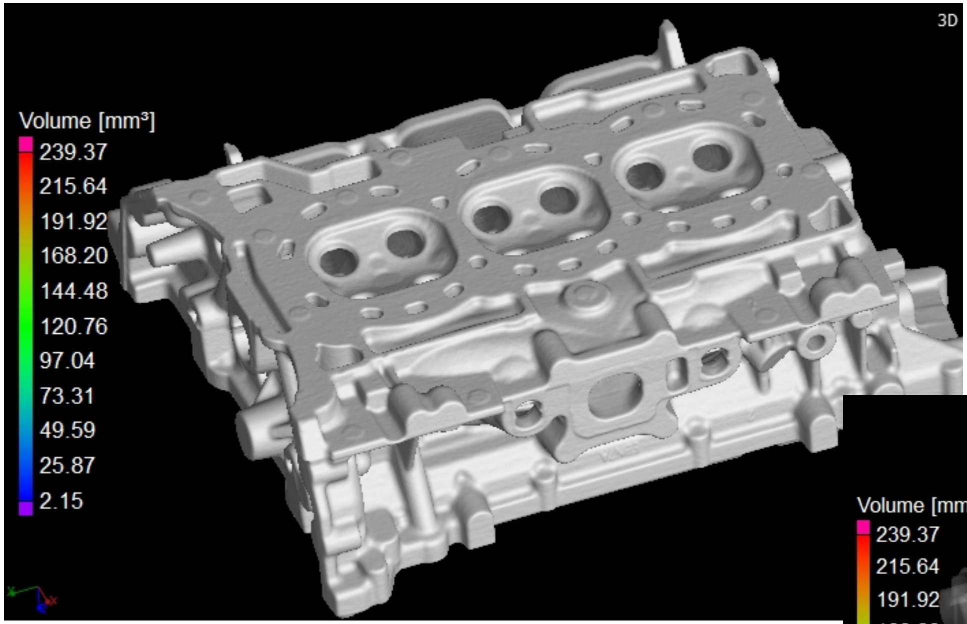
Prototyping: 1.5L GTDI Dragon Heads

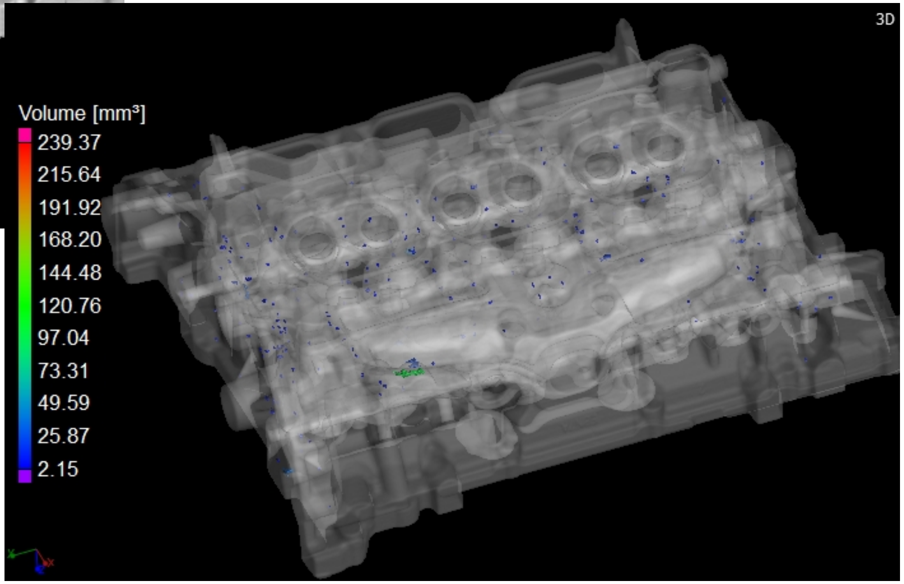
- Prototyping : conducted at Qin'an, China
- Alloys: AS7GU, Alcoa C3A1 and two Ford new alloys
- Castings: 50 castings per composition
- Sample locations: Deck Face with fast solidification rate, and Bolt Boss with slow solidification rate



Prototyping: 1.5L GTDI Dragon Heads

- **Castability verified by CT scan**



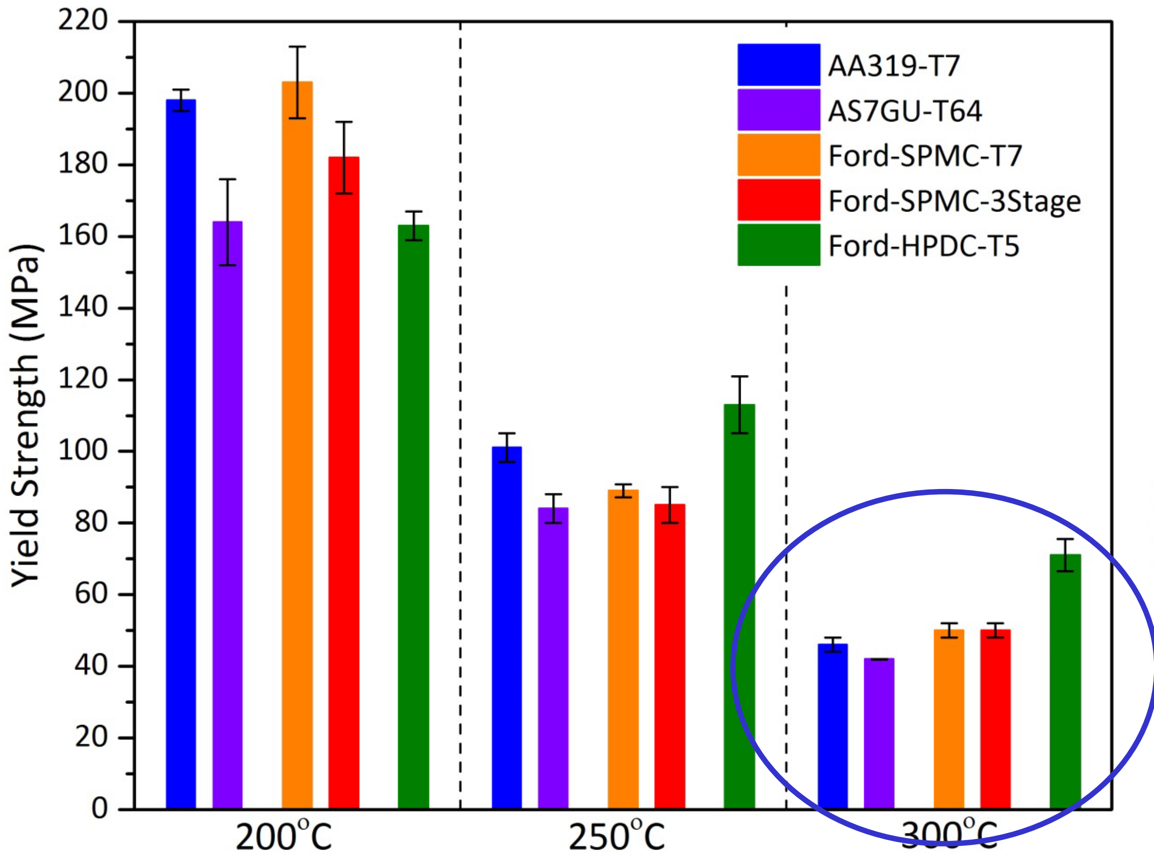


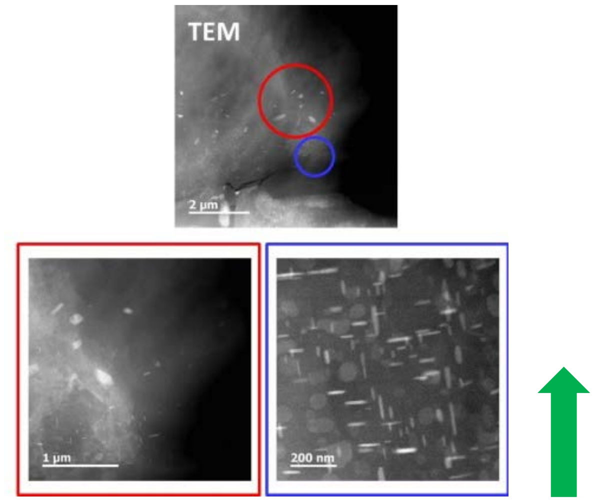
Prototyping: 2.0L GTDI Duratec Bearing Beam

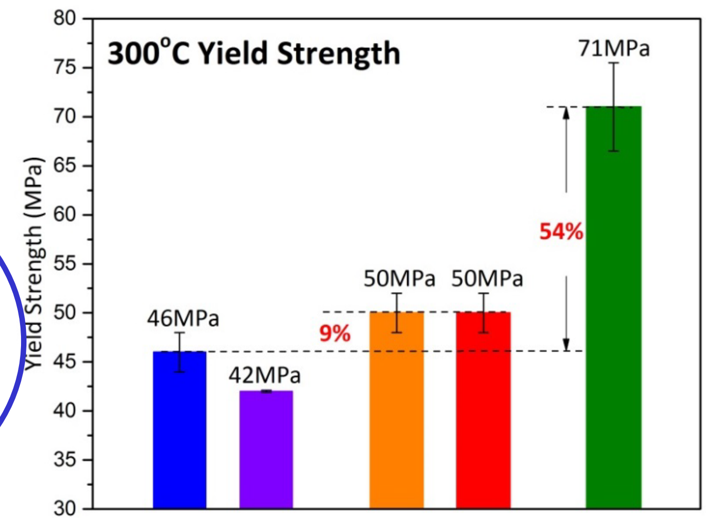
- Prototyping was conducted at Mag-tec, Jackson, MI
- Alloys: ADC12Z, Alcoa C667F and Ford-HPDC
- Castings: 200 Bearing Beams for each composition
- Sample locations: 5 locations for each Bearing Beam

Experiments: Elevated Temperature Tensile Properties

High-temperature quasi-static yield strength showing improved mechanical properties in Ford engine application alloys

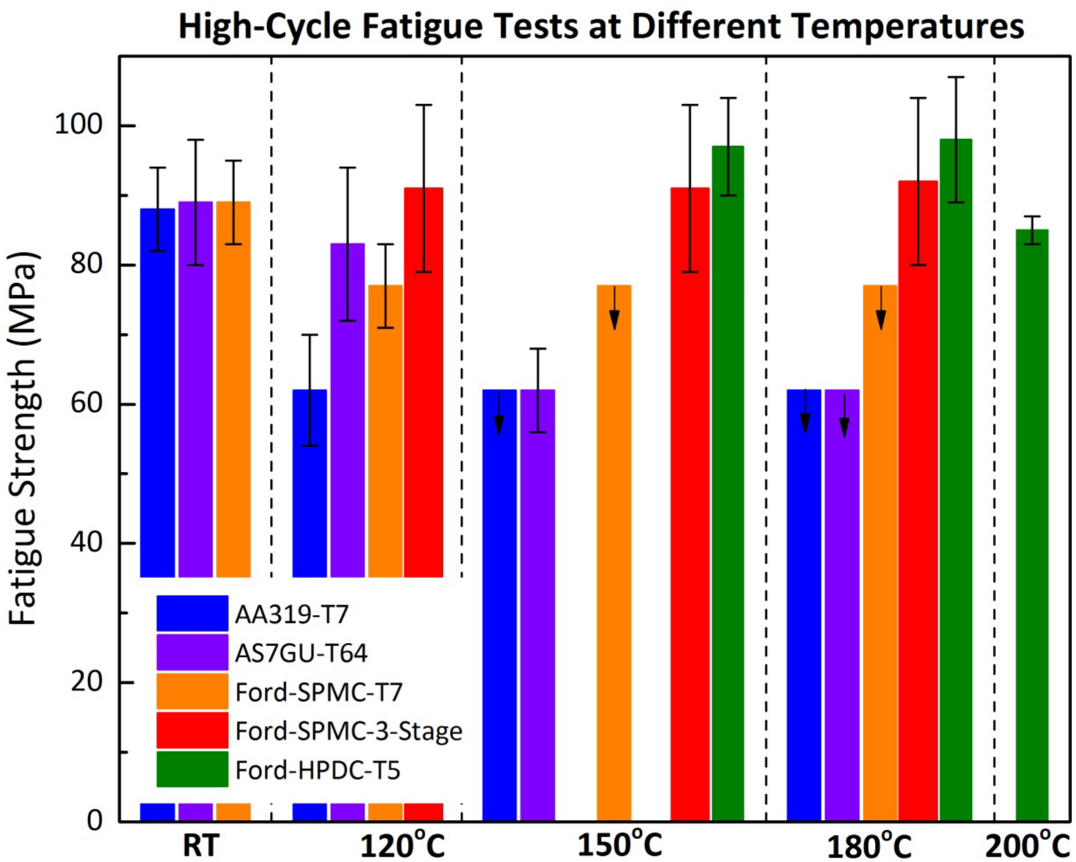


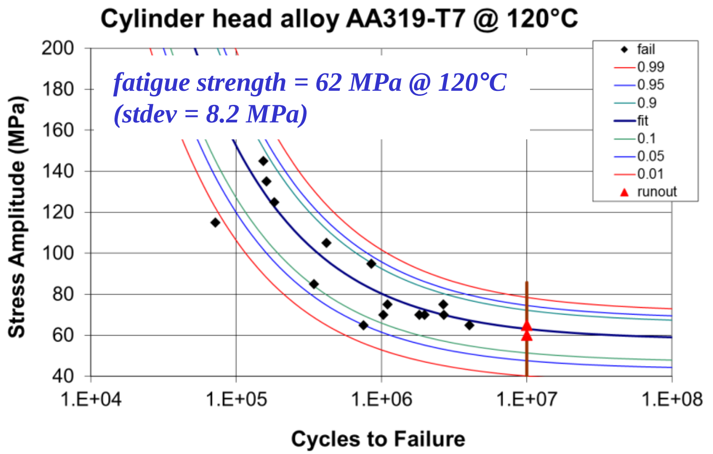


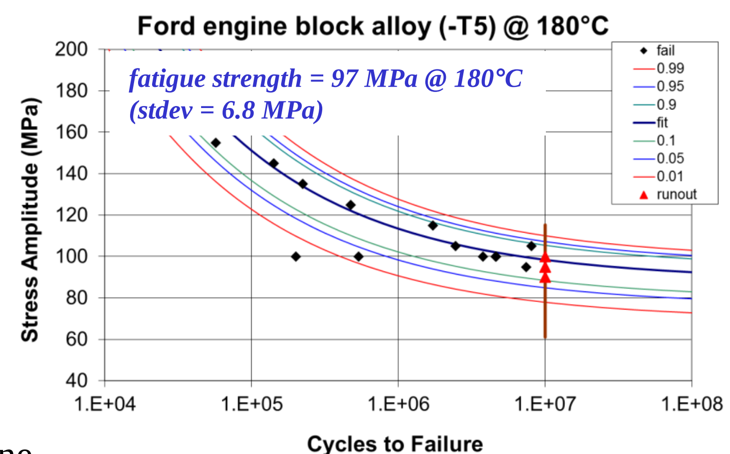


Experiments: Elevated Temperature Endurance Limit

Industry-first superior high-temperature high-cycle fatigue strength (>90MPa at 180°C) allows Ford to significantly advance engine design and performance and reduce TGWs



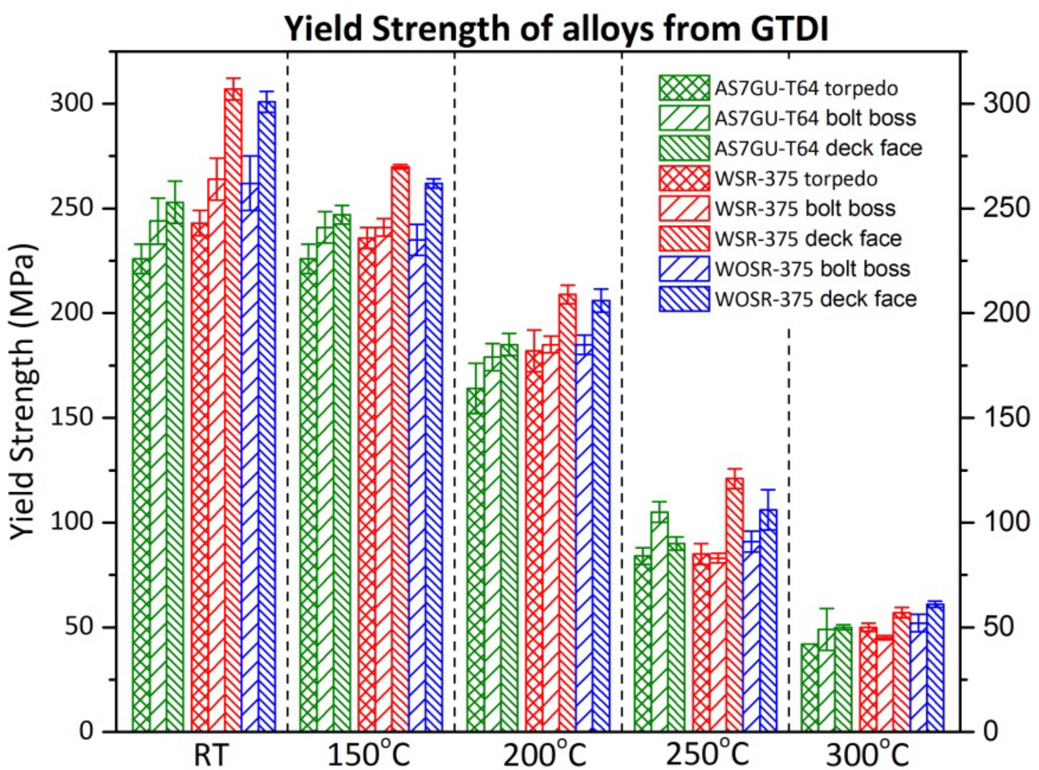




Patent application, "Advanced Cast Aluminum Alloys for Automotive Engine Application with Superior High-Temperature Properties," filed on July 28, 2017.

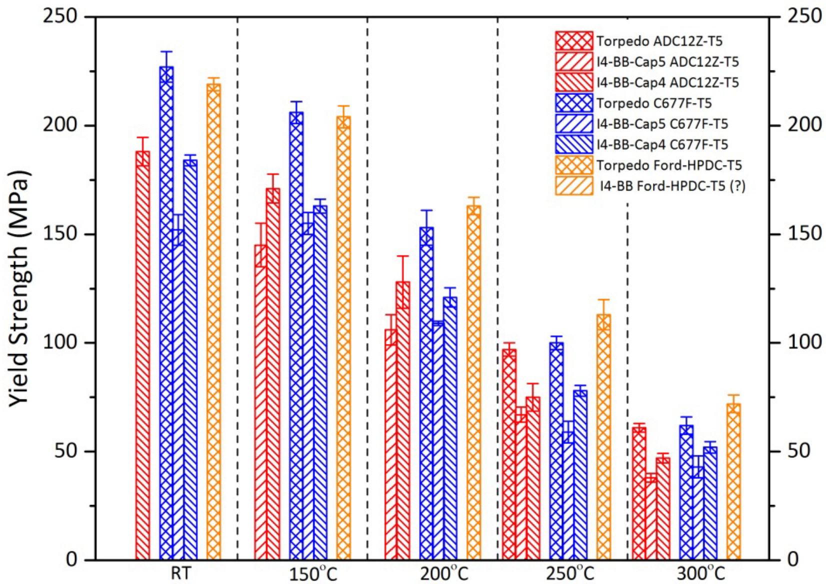
Prototyping: 1.5L GTDI Dragon Heads

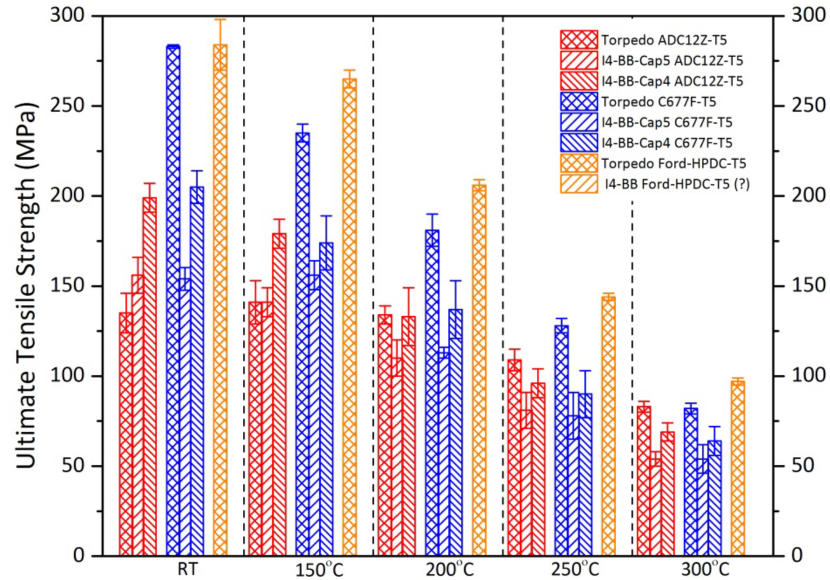
- **Yield strength (YS) and ultimate tensile strength (UTS)**
  - ➢ Deck face > Bolt boss ≈ test casting
  - ➢ Deck face: Ford new alloys > AS7GU
  - ➢ Bolt boss: Ford new alloys ≈ AS7GU

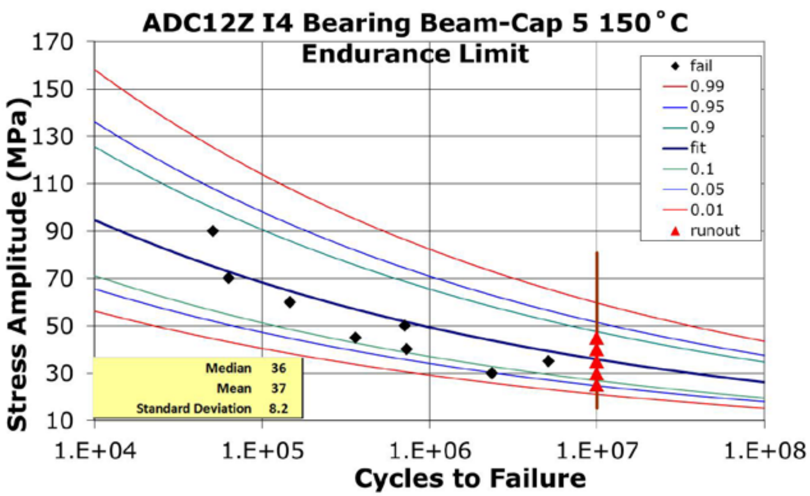


- **High cycle fatigue (HCF)**
  - ➢ HCF at 150°C:
    Ford new alloy ≈ AS7GU
    (~93MPa)
  - ➢ HCF at 180°C: Ford new alloy > AS7GU

Prototyping: 2.0L GTDI Duratec Bearing Beam



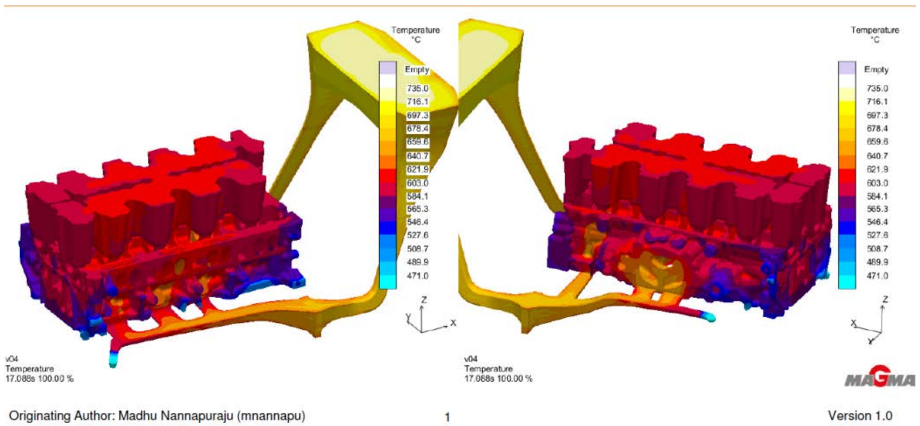


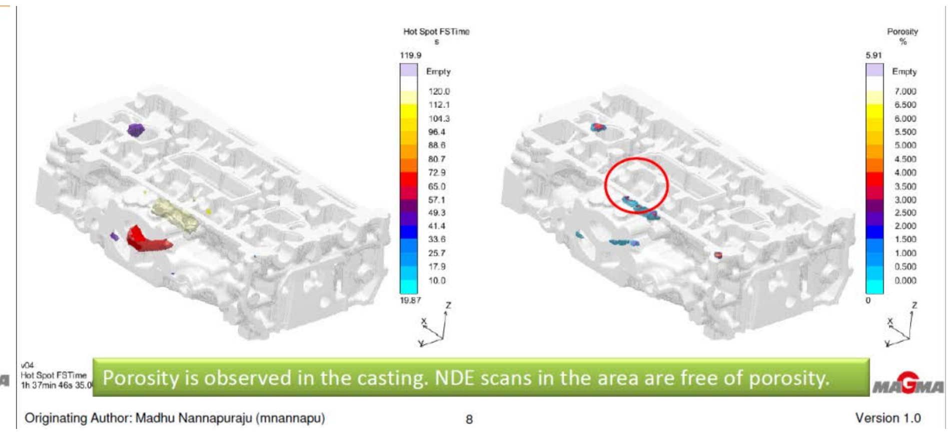


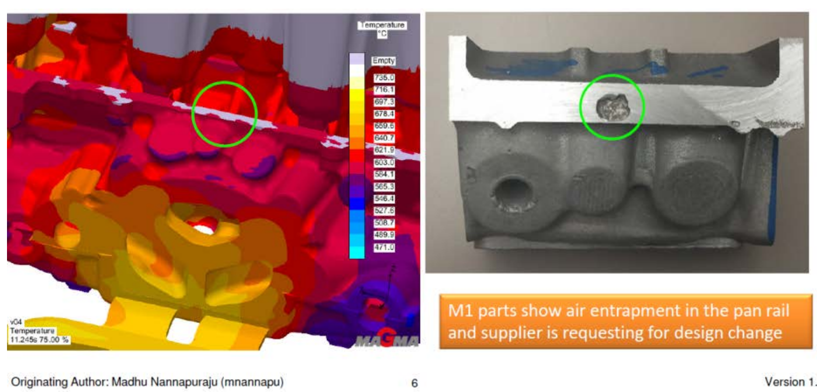
- **Low mechanical properties due to high level porosity**
- **Ryobi 380 is still below 40MPa**
- **HPDC castings at Ryobi at Japan**

Computational Tools Evaluation: Casting Process Sim.

- **MagmaSoft is untied to simulate the casting processes**
  - **GTDI Dragon Head, GTDI Duratec Bearing Beam, and Scorpion Head**
  - **Magmasoft has the full capability in casting process simulation**

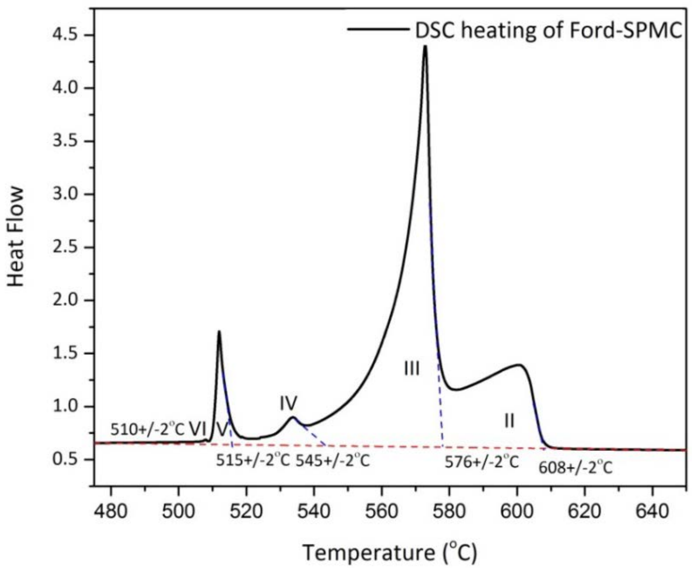






Computational Tools Evaluation: Solidification

- **Scheil Model predicted phase transition temperatures and solid phase fractions**
- **Phase transition temperatures & relative phase fractions can be measured by DSC**
- **Gap analysis: Scheil model predicted phase transition temperatures are off from DSC measurement**

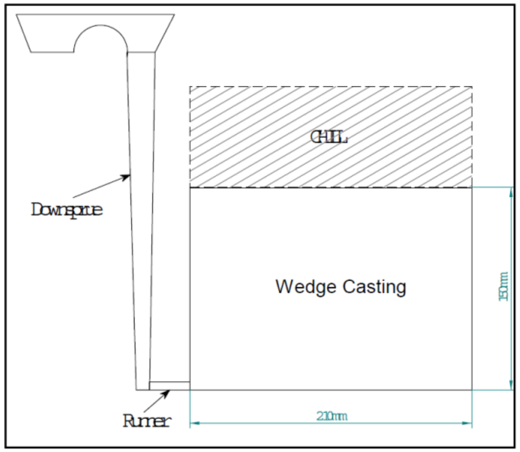


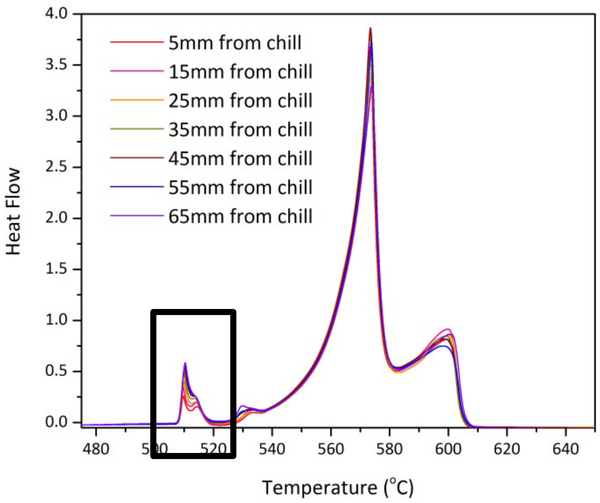
Temperature measured in DSC (°C)	Temperature predicted In Scheil (°C)	**Difference (°C)**	Formed Phases
N/A	690	**N/A**	$D0_{22}/D0_{23}$
608±2	591	**17**	Fcc_a1
576±2	557	**19**	Diamond_a4
545±2	515	**30**	Al9Fe2Si2
515±2	510	**5**	Al2Cu_C16
510±2	510	**0**	Q-AlCuMgSi

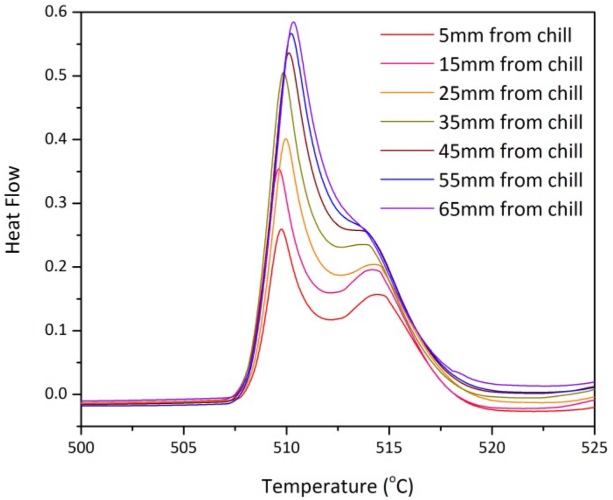
Computational Tools Evaluation: Solidification

- **DSC measurement shows the fraction of Theta_AlCu increases with decreasing of cooling rates**
- **The fraction of theta_AlCu in Scheil doesn't change with cooling rates**
- **Gap of Scheil Model: no cooling rates effect in considered in Scheil model**

Solid phases fraction						
$D0_{22}$	$D0_{23}$	fcc_a1	Diamond_a4	Al9Fe2Si2	Al2Cu_C16	Q_AlCuMgSi
0.28	0.57	86.82	6.16	0.58	5.02	0.56

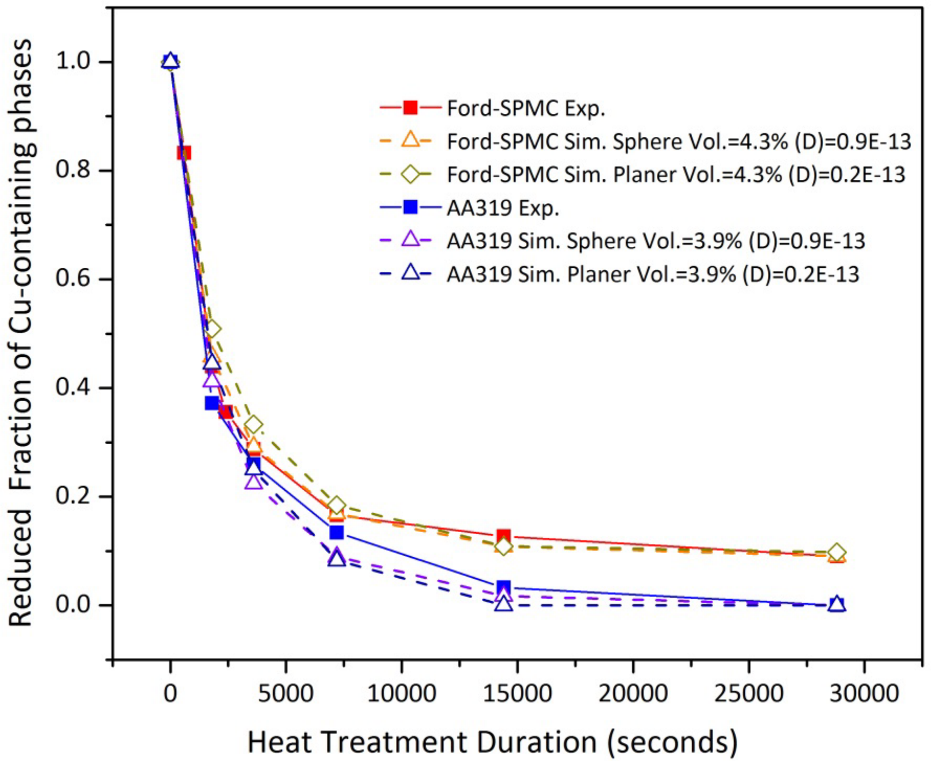






Computational Tools Evaluation: Solution Treatment

- **Reduce fraction is easy to obtain through simulation**
- **Simulated results show good agreement with DSC results**
- **Gap Identification:**
  - ➢ More reasonable geometry (cylinder and sphere2)
  - ➢ Zr and V can not be included in calculation
  - ➢ Optimization of mobility database



Computational Tools Evaluation: Spherical Precipitates

- **Kampmann and Wagner numerical method to solve Langer-Schwartz problem:**

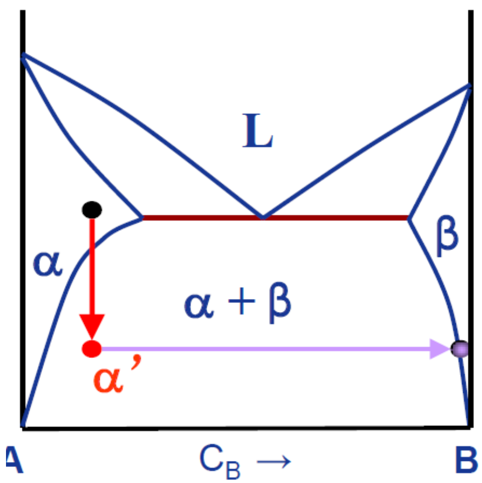
1st stage: Classic Nucleation Theory-homogeneous or inhomogeneous

- o $\frac{\partial f(r,t)}{\partial t} = -\frac{\partial}{\partial r}[v(r)f(r,t)] + j(r,t)$

2nd stage : Diffusion controlled continuity equation-Binary model, PrecipiCalc model, *et al*

- o $C_0^{\alpha} = C^{\alpha} + \left(C^{\beta} - C^{\alpha}\right)\int_0^{\infty}\frac{4\pi}{3}f(r,t)r^3dr$

3rd stage: Coarsening after $j(r,t)$ disappears: LSW model

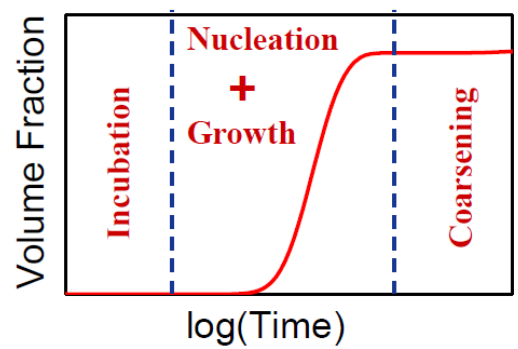


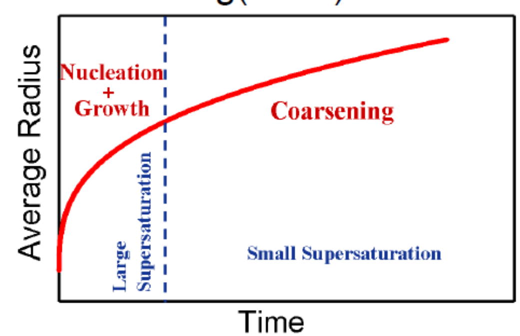
α’ → α + β

’ : matrix phase (supersaturated)

precipitate phase

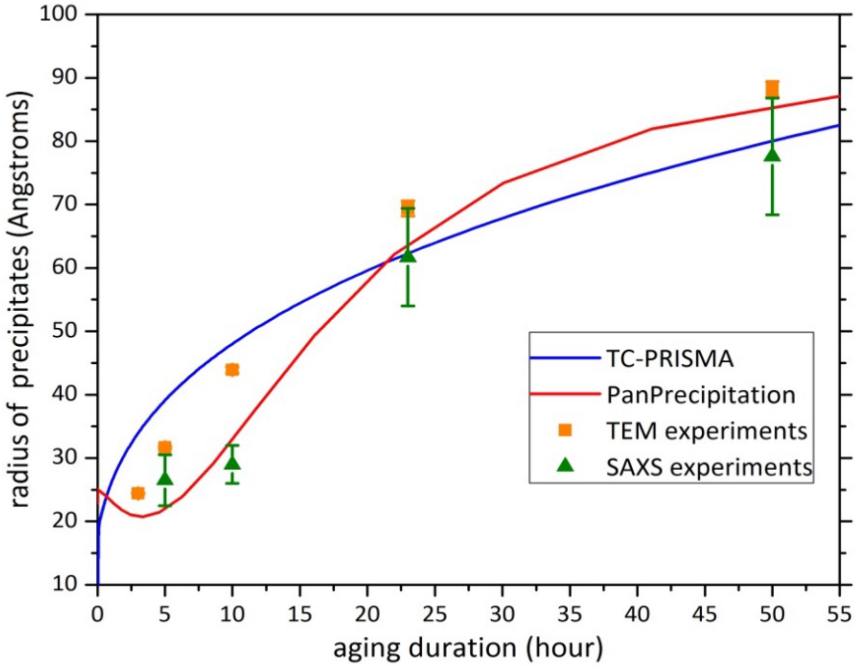
: stable solid solution

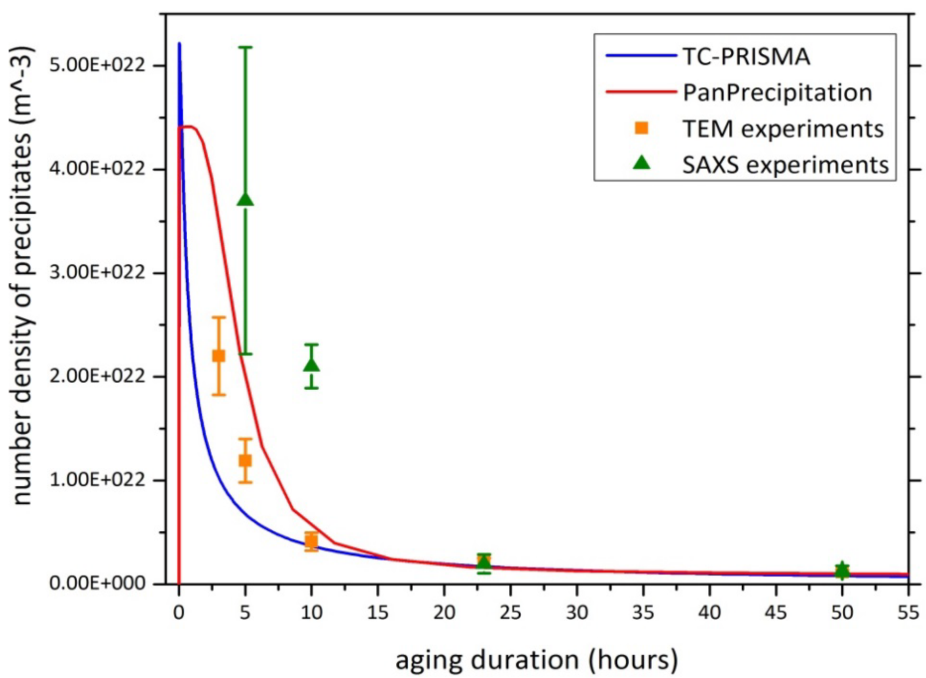




Computational Tools Evaluation: Spherical Precipitates

- PanPrecipitation from CompuTherm and TC-PRISMA from Thermo-Calc
- Thermodynamic database: TCAL5 and PanAl2016
- Mobility database: MOBAL3 and PanAl2016
- Kinetic databases are developed: Interfacial energy, strain energy nucleation site parameter, molar volume
- An enhance mobility parameter is added: Si can accelerate the kinetics of L12-Al3Zr Precipitates

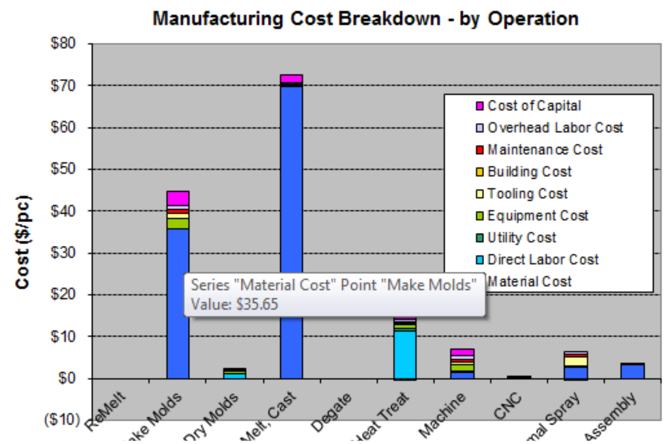




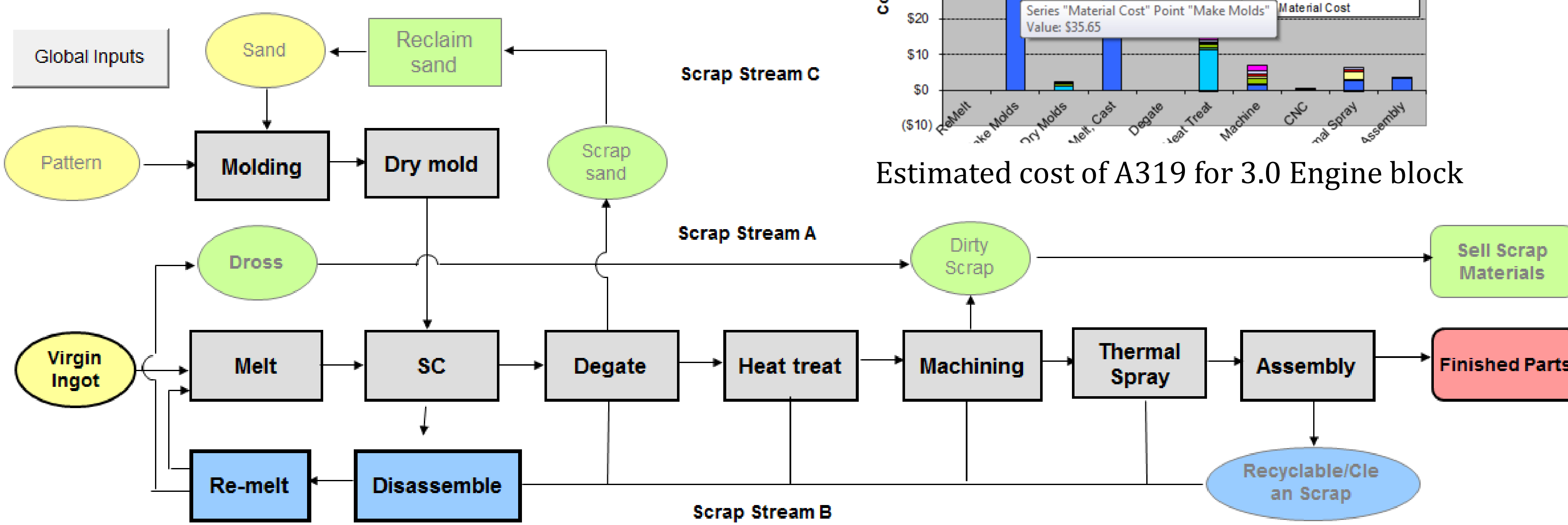
Cost Model Development

A sand casting cost model has been developed at Ford

- **The model covers melt, casting, heat treatment, machining, and so on**
- **Three alloys are evaluated: A319, AS7GU, and Ford-SPMC**
- **Melting and Heat treatment are critical**



Estimated cost of A319 for 3.0 Engine block



Conclusion

Summary

I. Successfully developed two novel combined alloy-heat treatment procedures for high temperature powertrain applications.

II. Demonstrated alloys performance on prototyped component

III. Evaluated several commercial ICME tools and Identify their Gaps